ASTRID-2: AN ADVANCED AURORAL MICROPROBE

Lars G. Blomberg, G. T. Marklund, Per-Arne Lindqvist, and Lars. Bylander

Alfvén Laboratory, Royal Institute of Technology, Stockholm, Sweden

ABSTRACT

Astrid-2 is an advanced auroral microprobe with dual primary mission objectives; to do high-quality *in situ* measurements of the physical processes behind the aurora, and to demonstrate the usefulness of microspacecraft as advanced research tools. Mission success will open up entirely new possibilities to carry out low-budget multipoint measurements in near-Earth space. This long-desired kind of *in situ* measurements are the next major step forward in experimental space physics. Astrid-2 has platform dimensions of 45 x 45 x 30 cm, a total mass of just below 30 kg, and carries scientific instruments for measuring local electric and magnetic fields, plasma density and density fluctuations, ions and electrons, as well as photometers for remote imaging of auroral emissions. Attitude determination is provided by a high-precision star imager. Some 250 Mbytes' worth of scientific data will be received each day at the two ground stations. Astrid-2 will be launched as a piggy-back on a Russian Kosmos-3M launcher into an 83 deg inclination circular orbit at 1000 km altitude. Nodal regression will give complete coverage of all local time sectors every 3.5 months.

BACKGROUND AND GENERAL INTRODUCTION

As a continuation of the successful Swedish minisatellite programme that produced the auroral research spacecraft Viking, 1986 (Hultqvist, 1990) and Freja, 1992 (Lundin *et al.*, 1994); a microsatellite programme was embarked upon in 1993. One of the ultimate goals of the microsatellite programme is to facilitate inexpensive multipoint auroral *in situ* measurements. The first microsatellite in the Astrid series, Astrid-1, was launched in January 1995, carrying an energetic neutral atom imager as its main payload. The flight was successful, and served as a proof of concept for a scientific microsatellite. Inspired by the success of Astrid-1, the second spacecraft in the series, Astrid-2, was given a project go-ahead in the spring of 1995. Astrid-2 carries a much larger payload than Astrid-1, and is focussed on diagnosing auroral processes in the Earth's upper atmosphere and ionosphere. Astrid-2 is intended as a proof of concept for auroral microsatellites, and includes innovative mechanisms that are further detailed below.

Astrid-2 will be launched as a piggy-back on a Kosmos-3M launcher from Plesetsk, Russia (N62.8, E40.3). The nominal orbit is circular at 1000 km altitude with an inclination of 83 deg. The initial right ascension of the ascending node will not be known until shortly before launch. However, relative to the Sun, the nodal regression rate is −1.7 deg/day, so in about 3.5 months all local times will be covered, regardless of the initial orientation.

The overall technical responsibility of the Astrid-2 mission is with the Swedish Space Corporation while the overall scientific responsibility is with the Alfvén Laboratory of the Royal Institute of Technology.

THE SPACECRAFT

The spacecraft platform is built by the Swedish Space Corporation, and is a box of dimensions 45 x 45 x 30 cm. With the solar panels deployted the dimensions are 170 x 110 x 30 cm. In addition, 7 booms will be deployed for the scientific instruments. The overall mass is 29 kg, of which almost 10 kg is payload. The spacecraft is spin-stabilized with a nominal spin rate of 10 rpm. There are 6 solar panels, two fixed ones and four deployable ones, which lie along the sides of the platform in their stowed position. Together they deliver a total of 90 W of power when sunlit. Since the solar panels all face in the direction of the spin axis, the spacecraft should be kept Sun-pointing to within 30 deg. The spacecraft surface including the solar panels is electrically conducting, to avoid differential charging and also to supply a sufficient area for the return current from spacecraft to plasma caused by current biasing of the electric field sensors, and by sweeps of the electric field and plasma density instruments. A picture of the Astrid-2 platform with deployed solar panels is shown in Figure 1.

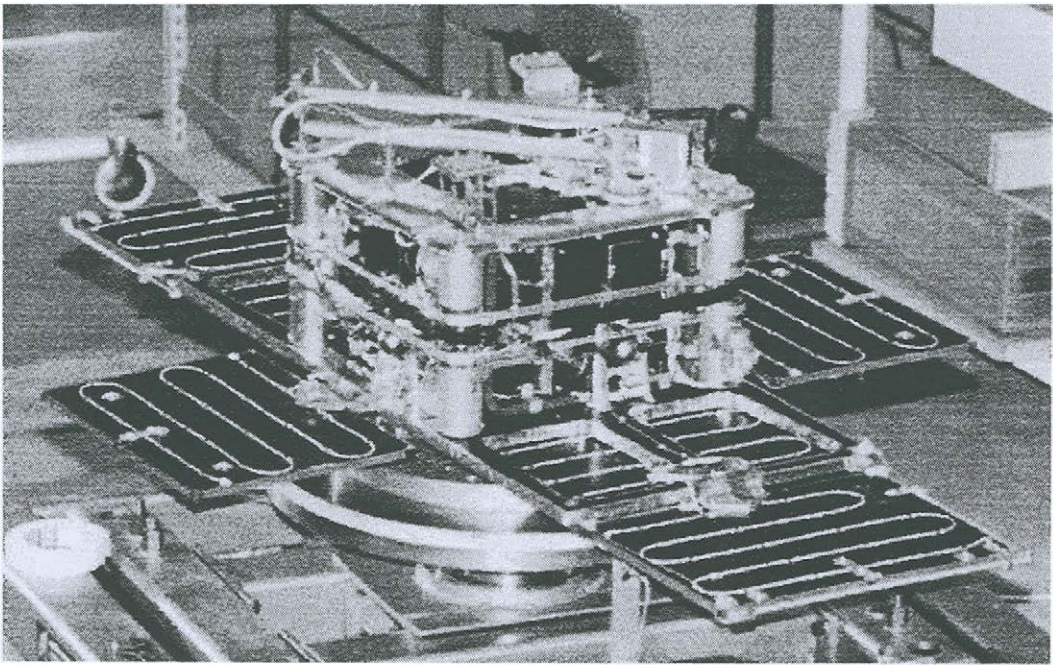

Figure 1. The Astrid-2 platform with deployed solar panels.

MISSION OBJECTIVES - SCIENTIFIC AND TECHNOLOGICAL

Astrid-2 has dual primary mission objectives. On one hand it is a fairly sophisticated research satellite, with scientific objectives related to the physics of the aurora. On the other hand it is a technological pioneering mission where a number of innovative techniques and mechanisms will be flight tested for the first time. If both mission objectives are fulfilled satisfactorily, the mission will serve as a proof of concept for small inexpensive auroral research probes. This will pave the way for affordable multi-spacecraft missions in the future.

Scientific Objectives

The advanced payload of Astrid-2 allows for a number of scientific topics to be addressed. Below we give a non-exhaustive list of examples of such topics.

Electrodynamics of Aurora and Black Aurora. The auroral acceleration processes are complex. A fairly recent discovery by the Freja spacecraft (Marklund *et al.*, 1994; 1997), subsequently studied also by the FAST team, was an anti-symmetry between the electric field structures in the upward field-aligned current region associated with auroral particles and those in the downward current region. Previously the downward current region was thought of as devoid of acceleration processes. Freja has demonstrated the existence of upward acceleration of electrons in these regions, with particularly strong transverse electric fields as a result. The strong transverse electric fields arise when current closes through ionospheric regions of low conductivity. The upward acceleration region is typically found at lower altitudes than the auroral acceleration regions, and we expect Astrid-2 to be able to contribute significant new observational data to shed additional light on the processes operating.

Physics of Transverse Ion Heating. Transverse ion heating is thought to be an important mechanism for ion outflow from the upper atmosphere. The heating often takes place at fairly low altitude, so, Astrid-2 is in a good position to measure *in situ* the fields, waves, and particle properties associated with the heating process.

Sources of the Cross-Polar Potential Drop. The cross-polar potential drop arises from the solar wind's interaction with Earth's magnetic field. Freja data have been used to study the relative importance of high and low latitude dynamos (Blomberg *et al.*, submitted manuscript, 1998). Astrid-2 will provide new valuable data that may deepen our understanding of the interaction mechanisms.

E-B Correlation and its Scale Size Dependence. Electric and magnetic fields associated with static structures in the ionosphere are often correlated. The electric field maps, at least partially, upwards along the geomagnetic field, and the field-aligned current produces a transverse magnetic disturbance field. Assuming complete mapping of the electric field the height-integrated ionospheric conductitvity may be inferred from the ratio of the magnetic to the electric field. At least for large scale sizes the electric field normally maps well between different altitudes. Studying the degree of correlation for smaller scale sizes may yield additional information about the ionosphere-magnetosphere interaction processes.

Global Mapping of $\mathbf{E}$, $j_{//}$. To understand the fundamental relationship between the ionospheric electric field and the field-aligned currents on the global scale, statistical pictures based on data from the same platform are needed (e.g., Blomberg *et al.*, 1992). Such pictures are normally not found in the literature. Astrid-2 is well instrumented and is in an ideal orbit to produce this kind of pictures.

Global Mapping of B. With a precision magnetometer and a star imager for attitude determination mounted back-to-back, Astrid-2 will be used as a complement to the Danish Oersted satellite, whose primary objective is to map the geomagnetic field.

Sub-auroral and Equatorial Electric Field Structures. Strong poleward directed electric fields are commonly observed at sub-auroral latitudes in the pre-midnight sector. They are believed to be associated with closure of field-aligned currents through an ionospheric region with depleted plasma density and, thus, low conductivity. For a recent overview of observational results see Karlsson *et al.* (1998).

Waves and Pulsations up to 1 kHz. With a maximum sampling rate of the field instruments of 2048 s^{-1} wave frequencies up to the local proton gyro frequency are covered. Thus, a multitude of pure wave as well as wave-particle interaction phenomena may be studied.

Technological Objectives

A number of new designs and mechanisms are to be flight tested on Astrid-2. Below are given a few examples of newly developed sub-systems.

Wire Boom Deployment Mechanism.

The wire booms used by the EMMA instrument (see also next section) are of a newly developed design (Hellman, 1996), where the booms in the stowed position are wound around the spacecraft body (Figure 2). Each of the four booms is wound two full turns, resulting in a boom length of 3.3 m, including a 0.1 m stub outside of the probe. The booms and probes are held by mechanisms at each corner of the platform and released by pyro firing. The deployment is driven by a step motor, located in one of the four legs of the platform structure. The total mass of the boom deployment system is less than 2 kg, to be compared with 3.5 kg per unit for conventional mechanisms.

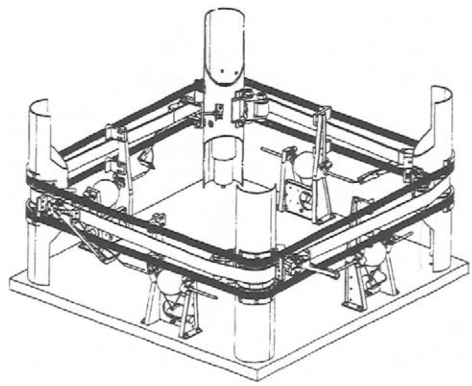

Figure 2. Schematic of the wire boom mechanism.

Star Imager for Attitude Determination.

Attitude determination will normally be performed by the on-board star imager which is a derivative of the Oersted star imager. The Astrid-2 design has been modified for use on a spinning platform. An accuracy of 1 arc sec for the spin axis and 20 arc sec for the spinning axes is foreseen. At times when the Earth is in the field of view of the star imager a new algorithm developed at Ålborg University for determining attitude based on magnetometer data will be employed.

Autonomous Ground Stations.

The ground stations to be used (further detailed below) are newly designed for the Astrid-2 mission. A high degree of autonomity has been a design driver. The ground stations will operate without manual intervention for extended periods of time. The controlling computer is remotely accessible and incoming data are time stamped using GPS time.

INSTRUMENTATION

There are 5 scientific instruments on-board Astrid-2. Together they form a fairly complete auroral physics payload. The instruments are:

- EMMA – Electric and Magnetic Monitoring of the Aurora.
- LINDA – Langmuir INterferomery and Density experiment for Astrid-2.
- MEDUSA – Miniaturized Electrostatic DUal-tophat Spherical Analyzer.
- PIA – Photometer for Imaging the Aurora.

• ASC – Advanced Stellar Compass.

All instruments are equipped with on-board memory, so that the sampled data can be stored temporarily for later transmission to ground. The location of the instruments on-board is shown in Figure 3.

EMMA

EMMA is an integrated electric field and magnetic field instrument performing simultaneous sampling of the potential of four electric field probes mounted on the wire booms in the spin plane (see above) and a tri-axial flux-gate magnetometer sensor mounted on the axial boom facing away from the Sun. Thus, the two spin plane components of **E** and the full **B** vector are measured simultaneously. In addition, since the electric probes are sampled individually, the spacecraft potential is continuously monitored giving information about the plasma density and also providing important information for the measurement of low-energy particles (which are attracted to or repelled from the detector if the spacecraft is at a different electrical potential from that of the plasma). The magnetometer sensor is mounted back-to-back with the star imager to maximize the precision of the spacecraft attitude knowledge for the scientific interpretation of the magnetometer data.

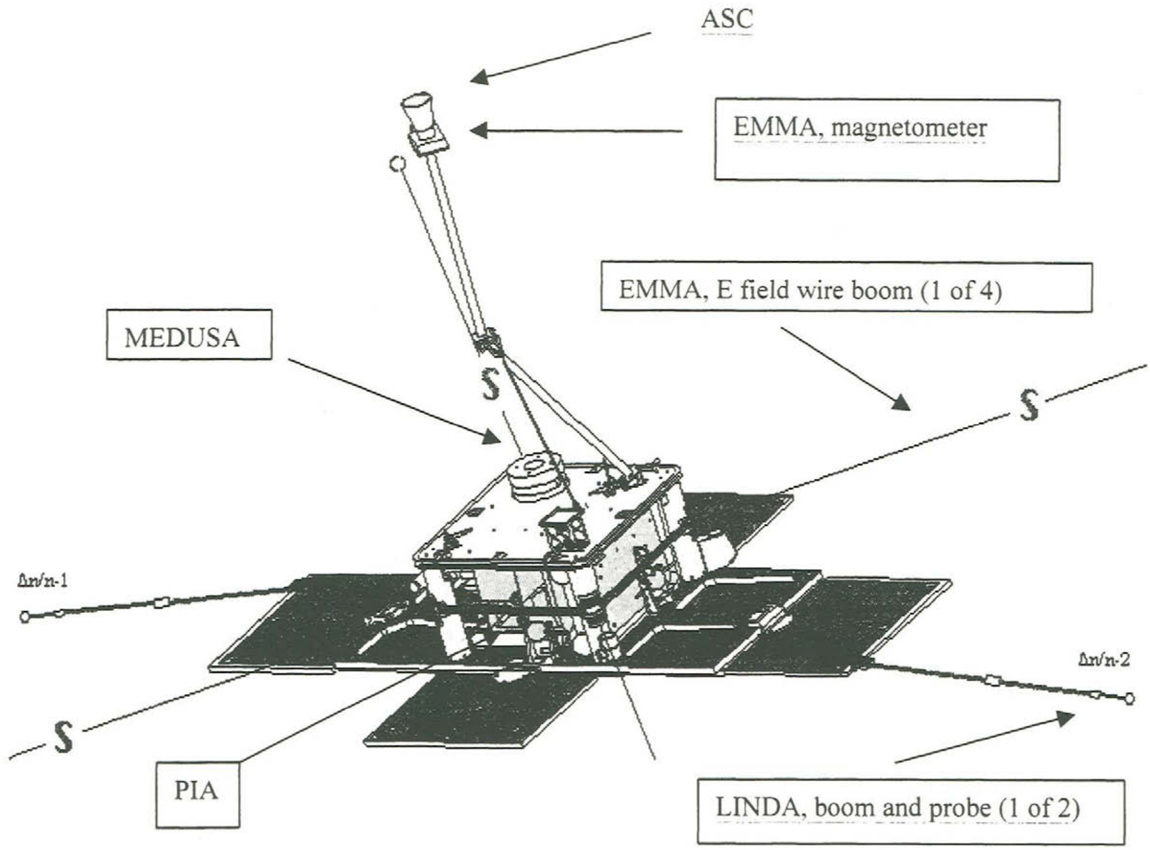

Figure 3. The Astrid-2 platform and instruments.

Sampling may be done at 16, 256, or 2048 samples/s. EMMA is equipped with a 12 MB semi-conductor memory for temporary storage of data outside times of contact with either of the ground stations. This memory is shared with the LINDA instrument (see below). In addition to passively monitoring the electric field, the probes may be actively swept in current or voltage to produce a current-voltage characteristic from which (at least in certain parameter regimes) information about plasma density, temperature, photo electron temperature, etc. may be derived.

The probes used for the electric field measurement are mounted on the 3.3 m long wire booms, have a diameter of 40 mm, and a titanium nitride (TiN) surface. TiN is used as surface material for the Langmuir probe on-board Cassini and is reported to work excellently. Because of the relatively short boom length the pre-amplifiers are located on the platform rather than inside the probes as is often the case when the booms are long.

The range of the measured electric field is ± 5 V/m, and the electric potentials are sampled with 16 bits resolution giving a bit resolution of 0.2 mV/m. The magnetic field is sampled with 20 bits resoultion. The range is ± 65,536 nT and the bit resolution 0.125 nT.

EMMA is built by the Alfvén Laboratory of the Royal Institute of Technology, Stockholm together with the Technical University of Denmark, Lyngby.

More details about the EMMA instrument can be found in Marklund *et al.* (1997) and in Blomberg *et al.* (1997).

LINDA

LINDA measures plasma density at up to 16 samples/s and density fluctuations at up to 8192 samples/s. The latter corresponds to a spatial resolution of about 1 m. With two Langmuir probes mounted on 0.8 m booms, which in the stowed position lie along the edges of the solar panels, interferometric measurements of moving plasma structures are possible. Voltage sweeps of the probes are also possible which yield information on plasma parameters as discussed above (EMMA subsection). LINDA is controlled by the same CPU as EMMA and the two instruments share on-board memory. Because of the high sampling rate a snapshot scheme will be used for data collection, where segments of the full wave form are captured intermittently. Also the LINDA probes have a TiN surface.

LINDA is built by the Swedish Institute of Space Physics, Uppsala.

MEDUSA

MEDUSA measures ions and electrons simultaneously in the spacecraft spin plane. There are 16 sectors in the plane of acceptance, and the maximum particle energy that can be detected is 18 keV per unit charge. For electrons up to 16 energy sweeps/s can be made. The corresponding figure for ions is 8 sweeeps/s. A variety of modes with lower resolution may be used to acquire overview data during prolonged periods of time.

MEDUSA is built by the Swedish Institute of Space Physics, Kiruna together with Southwest Research Institute, San Antonio, Texas.

PIA

PIA consists of three photometers. Each photometer measures four pixels and has a focal length of 250 mm. Two of them are mounted in the spin plane for spin-scanning imaging of auroral emissions. The sensors are sensitive to emissions in the wavelength band 125-150 nm, thus, in the case of aurora mainly oxygen emissions will be recorded. The third photometer is looking along the spin axis, hence, approximately in the Sun direction, is sensitive to Lyman α emissions (121 nm), and will mainly be used for atmospheric absorption studies. The sampling rate of the photometers is 256 s^{-1}.

PIA is built by the Max-Planck-Institut für Aeronomie, Lindau together with the Swedish Institute of Space Physics, Kiruna.

ASC

The ASC is a derivative of the star imager developed for the Oersted mission. The major difference from the Oersted mission is that the Astrid-2 platform is spinning, and thus, each star will show up as an arc segment rather than as a point on the image. The ASC uses CCD detectors for the imaging, and an on-board star catalogue, so that absolute values of the attitude are put directly into the telemetry. No post-processing on the ground will be needed. The attitude will be determined with an accuracy of 1 arc sec for the spin axis and 20 arc sec for the spinning axes.

The ASC is built by the Technical University of Denmark, Lyngby.

GROUND STATIONS AND TELEMETRY

Two ground stations will be employed for the Astrid-2 project (Figure 4). The primary ground station is located at the roof of the Swedish Space Corporation building in Solna, Sweden (N59.3, E18.0). On average the spacecraft will be above the Solna horizon about 2 hours per day. All commanding of the spacecraft will be done from this ground station. The second ground station is located on the South African base SANAE IV on the Antarctic continent (S71.1, W02.8), see Figure 5. Because of the higher latitude the contact time is longer at SANAE IV than in Solna, about 2.5 hours per day on average. The SANAE IV station is downlink only, no commanding is possible from there.

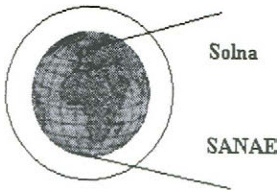

Figure 4. Location of the Astrid-2 ground stations.

The telemetry uses S-band, BPSK, and Viterbi-encoding, and has a net data rate of 128 kbits/s for the downlink, and 4.8 kbits/s for the uplink. With 4.5 hrs of contact time a data volume of approximately 250 MB can be transferred each day from spacecraft to ground. From the Solna station data are accessible to the instrument groups in real-time through Internet, and real-time commanding of the instruments is also possible. From the SANAE IV station a small subset of the data received may be retrieved via modem, but the primary means of data transfer is by ship, during the summer months when SANAE IV is accessible.

The ground station at SANAE IV has been set up in collaboration with the Physics Department of the University of Natal, Durban, and will be operated by their resident expedition members. Joint studies of Astrid-2 data and ground-based observations from SANAE IV's scientific instrumentation are planned.

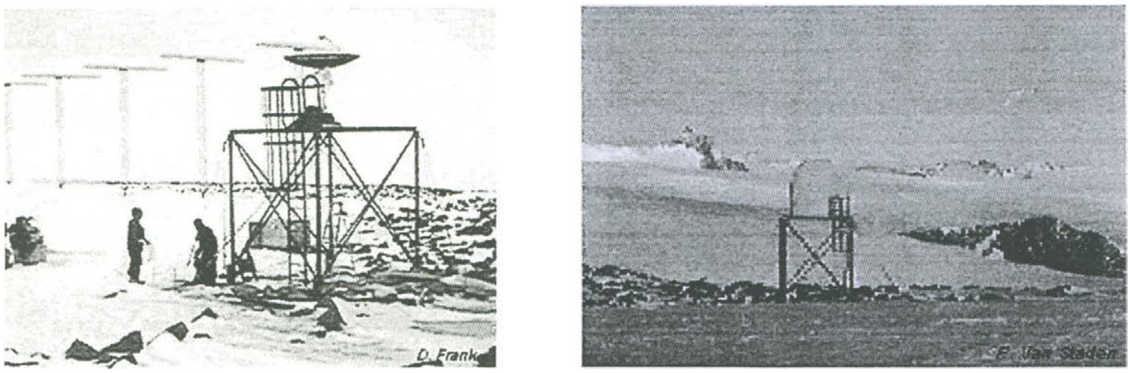

Figure 5. The telemetry station at SANAE IV (left, during construction; right, completed).

IN-FLIGHT OPERATIONS

All instruments are designed to allow continuous operation. Both the instruments and the platform have also been designed to run without operator intervention for prolonged periods of time. Instrument commands may be uploaded in bulk to the Astrid-2 System Unit (ASU) for later execution. Power, attitude and spin control are all autonomous.

Two basic modes are planned; one with low resolution of the measured quantities, normally to be used at low latitudes and at times when consecutive ground station contacts are well separated in time; the other with medium resolution, normally to be used at auroral and higher latitudes. Nominally, in the low resolution mode EMMA will take 16 samples/s of **E** and **B**, LINDA will sample the absolute density but not density fluctuations, MEDUSA will sample particle fluxes in three directions, parallel, perpendicular, and anti-parallel to **B**, and PIA will not operate. Nominally, in the medium resolution mode, EMMA will sample at 256 s^{-1}, LINDA will sample density at 16 s^{-1}, and take snapshots of dn/n at 8192 s^{-1}, MEDUSA will sample all 16 sectors in the spin plane, and PIA will take 256 photometer samples/s. The ASC is foreseen to operate at all times when it has an unobstructed view of the sky.

In addition to the two basic modes, the instruments will at times be operated in a high resolution mode. In this mode EMMA samples at 2048 s^{-1}, LINDA samples dn/n at 8192 s^{-1} but with either more frequent or longer snapshots than in the medium resolution mode, while MEDUSA and PIA operate in the same way as in the medium resolution mode.

Data dumping will be done interchangingly at the two ground stations, so that northern as well as southern hemisphere data are dumped at both stations. This is required for operational reasons since the ground station contacts alternatingly occur before and after the high-latitude pass where the on-board memory fills up because the instruments are run at higher resolution. The long delay time in receiving the full Antarctic data set must also be taken into consideration. For example, data from campaigns run jointly with other instrument sets will normally be dumped at Solna.

DATA HANDLING AND ANALYSIS

The data received at the Solna station will be available to the instrument groups in real time. They will also be transferred electronically to the data archive at the Alfvén Laboratory directly after each pass. Data received at SANAE will be stored on DAT tapes. The DATs will be transported out of SANAE by ship when the ice conditions permit it.

Astrid-2 Summary Plots (ASP) will be made available on the World Wide Web within a day or two of receiving the data. A fairly sophisticated IDL based analysis software package has been developed for the scientific analysis. To facilitate easy data exchange intermediate data files are in ASCII format.

SUMMARY

Astrid-2 is the first complete microspacecraft for auroral research, featuring new developments for the platform as well as for the scientific instruments. Primary mission objectives are to do high-quality auroral research and to demonstrate the feasibility of using microspacecraft for this kind of science. If these objectives can be met successfully, it will open up brand new possibilities to perform inexpensive multipoint measurements of auroral processes. The spacecraft may also be operated at a low cost because of the many autonomous systems on-board as well as on the ground. Since operations are not a cost driver we expect to be able to operate the spacecraft beyond its nominal one year life time, if it still functions properly.

ACKNOWLEDGEMENTS

The Astrid-2 project is funded by the Swedish National Space Board and by corresponding agencies in the other participating countries. The Antarctic ground station is mainly funded through donations from the Wallenberg Foundation and from the Royal Institute of Technology We wish to acknowledge the many scientists and engineers who have contributed to this project in different ways. The pictures of the Antarctic ground station are by courtesy of the SANAE IV team.

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